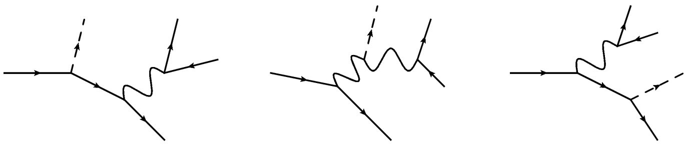
Higgs from the Top[1]

Snowmass Energy Frontier Workshop, BNL

Richard Ruiz

Pitt-PACC, University of Pittsburgh

April 3, 2013



[1] With T. Han (Pitt.). To appear soon.

Motivation for New Higgs Physics

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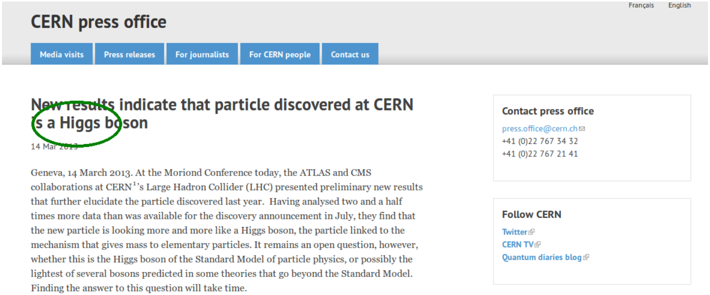
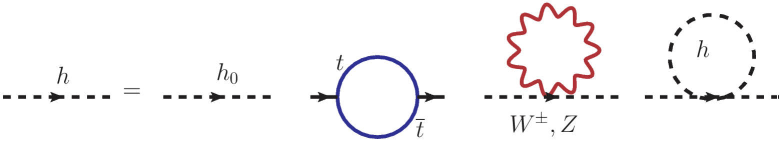


- A new particle has been discovered.
- **The Definite Article Problem**:
  - Should there be a "the" in this press release?

E.g., The SM Higgs Boson Mass is Poorly Understood

Radiative corrections to Higgs tree-level mass are quadratic, not logarithmically (technically natural): It is very divergent.

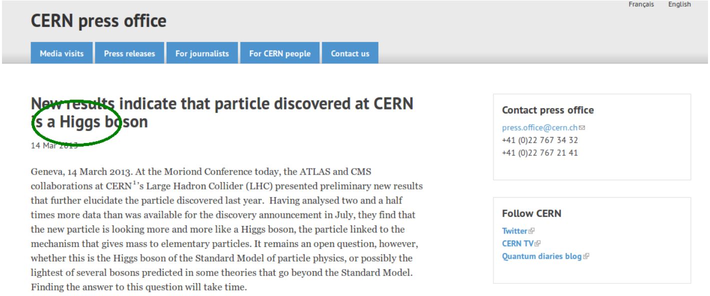


$$\underbrace{m_h^2}_{\text{direct obs.}} = \underbrace{m_0^2}_{\text{bare, unstable}} - \frac{3}{8\pi^2}\underbrace{y_t^2}_{m_t}\Lambda^2 + \frac{1}{16\pi^2}\underbrace{g^2}_{m_Z,\alpha_{EM}}\Lambda^2 + \frac{1}{16\pi^2}\underbrace{\lambda^2}_{m_h, G_F}\Lambda^2$$

- The Higgs boson's mass is too small and (technically) unnatural.
- Naively, we expect Λ is at Planck scale, $\Lambda_{pl} \sim 10^{19}$ GeV
- $\Lambda \sim 10$ TeV leads to $\sim 95\%$ cancellation to obtain 126 GeV:

$$m_h^2 = m_0^2 + \left[-(2\ TeV)^2 + (0.5\ TeV)^2 + (0.1\ TeV)^2 \left(\frac{\Lambda_{t,W/B,H}}{10\ TeV} \right)^2 \right]$$

CERN press office: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New results indicate that particle discovered at CERN is a Higgs boson

14 Mar 2013

Geneva, 14 March 2013. At the Moriond Conference today, the ATLAS and CMS collaborations at CERN[1]'s Large Hadron Collider (LHC) presented preliminary new results that further elucidate the particle discovered last year. Having analysed two and a half times more data than was available for the discovery announcement in July, they find that the new particle is looking more and more like a Higgs boson, the particle linked to the mechanism that gives mass to elementary particles. It remains an open question, however, whether this is the Higgs boson of the Standard Model of particle physics, or possibly the lightest of several bosons predicted in some theories that go beyond the Standard Model. Finding the answer to this question will take time.

Contact press office

press.office@cern.ch
+41 (0)22 767 34 32
+41 (0)22 767 21 41

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- A new particle has been discovered.
- **The Definite Article Problem**:
  - Should there be a “the” in this press release?
- *Our* Higgs boson is worth studying much further.

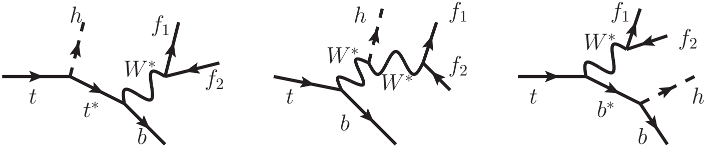
Outline

Synopsis: *In light of the discovery of a SM-like Higgs boson, we have systematically studied the rare $t \to Wbh$ decay process in the context of the Standard Model (SM), the Two Higgs Doublet Model (2HDM), and Effective Field Theory (EFT) . We report that the effects of new physics can both considerably enhance and suppress this kinematically accessible decay rate, relative to the SM.*

- Motivation ✓
- Why $t \to Wbh$? (1 Slide) $\leftarrow$ *Next*!
- What the Standard Model Says (1 Slide)
- Two New Physics (NP) Scenarios:
  - 2 Higgs Doublet Model: Type II [2HDM(II)]
  - Effective Field Theory: Gauge Inv. dimension-six operators
- LHC Prospects (1 Slide)
- Summary (1 Slide)

Four Arguments for $t \to W^* bh \to \mu\nu_\mu bh$.

1. July 2012's discovery implies $m_t > m_h + m_b + m_\mu + m_\nu$
   - This previously unobserved decay, however rare, *exist*. Period. [*Rizzo* (1987); *Barger, Keung* (1988); *Mahlon, Parke* (1995)]



2. Dependant on both *tth* (leading) & *WWh* (subleading) vertexes
   - Sensitive to a litany of new physics effects.
3. The LHC is a top factory!
   - $\sigma^{NLO}_{LHC14}(t\bar{t}) = 830$ pb. $\mathcal{L} = 100$ fb/yr $\implies$ 83 million pairs/yr!
4. Most sensitive way to measure *tth* coupling at LHC.
   - $pp \to tth$ production has reco. difficulties and poor S/N

The Standard Model (SM) Prediction

A SM Higgs boson at $m_h = 126$ GeV kinematically allows

$$t \to W^{+*} bh, \qquad W^{+*} \to \mu^+ \nu_\mu$$

Following Mahlon & Parke [PLB347, 394 (1995)], $\Gamma(t \to Wbh)$ is defined by

$$\Gamma(t \to Wbh) = \frac{\Gamma(t \to \mu^+ \nu_\mu bh)}{BR(W \to \mu^+ \nu_\mu)}$$

The $BR(t \to Wbh)$ is then

$$BR(t \to Wbh) = \frac{\Gamma(t \to Wbh)}{\Gamma(t \to Wb)}$$

Using CalcHEP 3.4.2, we find excellent agreement with M&P. Inputing updated parameters[2], the SM predicts

$$BR(t \to Wbh) = 1.65 \times 10^{-9}$$

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[2] $m_t = 173.5$ GeV, $m_b^{\overline{\text{MS}}}(m_t) = 3.03$ GeV, $BR(W \to \mu\nu) = 10.57\%$, etc.

Outline

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- Motivation ✓
- Why $t \to Wbh$? (1 Slide) ✓
- What the Standard Model Says (1 Slide) ✓
- Two New Physics (NP) Scenarios: ← *Next!*
  - 2 Higgs Doublet Model Type II [2HDM(II)]
  - Effective Field Theory: Gauge Inv. dimension-six operators
- LHC Prospects (1 Slide)
- Summary (1 Slide)

Two Higgs Doublet Model: Type II[3]

[3] For review of 2HDM, see Gunion, et. al., *Higgs Hunter′s Guide*, and Branco, et. al. *arXiv* : 1106.0034 [*hep* − *ph*].

Two Higgs Doublet Model Type II [2HDM(II)] in a Nutshell

Two complex $SU(2)_L$ doublets with $U(1)_Y$ hypercharges and vevs.

$$\langle\Phi_u\rangle = \frac{v_u}{\sqrt{2}},\ \langle\Phi_d\rangle = \frac{v_d}{\sqrt{2}}$$

$$v^2 = v_u^2 + v_d^2, \quad \tan\beta \equiv v_u/v_d$$

Just like the SM... with more degrees of freedom:

2 CP-even: H_1, H_2; 1 CP-odd: A^0; 1 $U(1)_{EM}$ charged: $H^\pm$

In total, there are 6 free parameters: 4 masses, $\tan\beta$, $\sin\alpha$

2HDM(II) Couplings

In the SM, after EWSB, the Higgs coupling terms appear like

$$\mathcal{L} \ni -\frac{gm_u}{2M_W}\overline{u_L}u_R h - \frac{gm_d}{2M_W}\overline{d_L}d_R h + h.c. + gM_W W_\mu W^\mu h.$$

In 2HDM(II), after EWSB, the **same** couplings exist, just with more degrees of freedom:

$$\begin{aligned}\mathcal{L} \ni &-\frac{gm_u}{2M_W}\overline{u_L}\left(H_1\frac{\cos\alpha}{\sin\beta} + H_2\frac{\sin\alpha}{\sin\beta} - i\gamma^5 A^0\cot\beta\right)u_R \\ &-\frac{gm_d}{2M_W}\overline{d_L}\left(-H_1\frac{\sin\alpha}{\cos\beta} + H_2\frac{\cos\alpha}{\cos\beta} - i\gamma^5 A^0\tan\beta\right)d_R + h.c. \\ &+ gM_W W_\mu W^\mu\left[H_1\sin(\beta-\alpha) + H_2\cos(\beta-\alpha)\right].\end{aligned}$$

If H_1 is (arbitrarily) associated with the SM Higgs, one recognizes 2HDM(II) Higgs couplings as scaled SM couplings:

$$\frac{g_{uuH_1}}{g_{SM}} = \frac{\cos\alpha}{\sin\beta}, \quad \frac{g_{uuH_1}}{g_{SM}} = -\frac{\sin\alpha}{\cos\beta}, \quad \frac{g_{WWH_1}}{g_{SM}} = \sin(\beta-\alpha)$$

2HDM(II) Couplings and LHC Data

ATLAS and CMS observations of a SM-like[4] Higgs boson at 126 GeV tell us two things:

- 1 CP-even mass eigenstate is fixed, and
- Either $\sin(\beta - \alpha)$ or $\cos(\beta - \alpha)$ is close to 1.

Without loss of generality, we define the SM-likeness parameter Δ_V such that[5]

$$\sin(\beta - \alpha) \equiv 1 - \Delta_V, \quad 0 < \Delta_V < 1$$

Double angle formulae allow us to replace the CP-even mass mixing parameter, α, with Δ_V, which we know.. roughly.

$$\Delta_V = 0.1 \implies H_1 \text{ is SM-like, } H_2 \text{ is SM-unlike}$$

$$\Delta_V = 0.9 \implies H_2 \text{ is SM-like, } H_1 \text{ is SM-unlike}$$

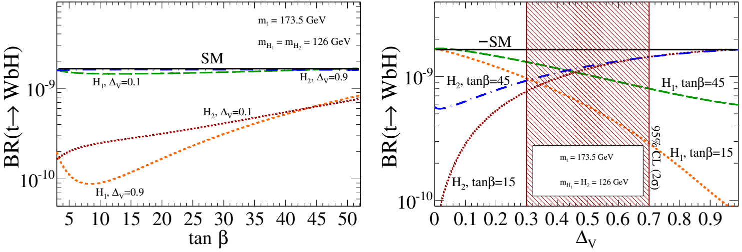
I will save you further details and just jump to plots!

[4] *WWh* coupling is close to SM value.

[5] C.W. Chiang, K. Yagyu *arXiv* : 1303.0168 has an identical parameterization.

2HDM(II) Branching Ratios

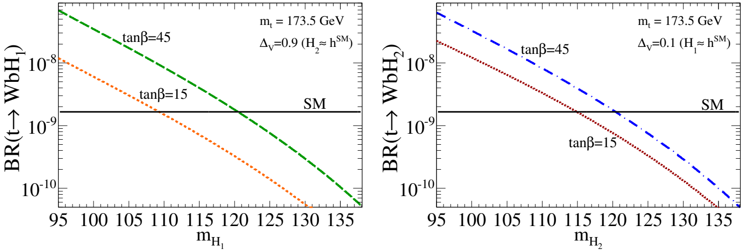
Branching Ratio as a function of SM-likeness, Δ_V, and $\tan\beta$.
Black line is prediction for SM Higgs with SM couplings.
$m_{H_1} = m_{H_2} = 126$ GeV



- Dips in $\tan\beta$ dependence are indicative of playoff between ttH and bbH couplings
- Relationship between H_1 and H_2 demonstrates the generic 2HDM sum rule: $g^2_{WWH_1} + g^2_{WWH_2} = g^2_{WWh^{SM}}$

2HDM(II) Branching Ratios

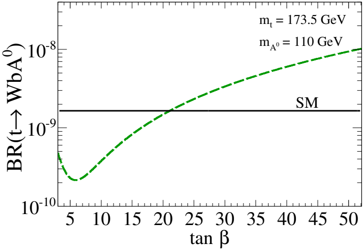
Branching ratio of SM-unlike Higgs boson vs mass.
Black line is prediction for SM Higgs with SM couplings.
SM-like Higgs boson mass fixed at 126 GeV

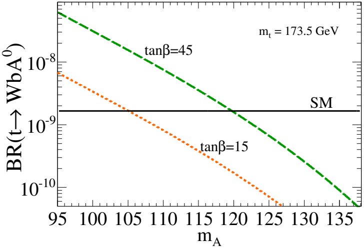


- Coupling suppression from being SM-unlike is compensated by the vast increase in available phase space

2HDM(II): Sensitivity to low mass CP-Odd Higgs, A^0

Branching Ratio as a function of $\tan\beta$ and m_A
Black line is prediction for SM Higgs with SM couplings.





- $\uparrow \tan\beta \implies \downarrow ttA, \uparrow bbA$ couplings $\implies \uparrow BR$ at high $\tan\beta$
- High rates (vs SM) in parameter space "sweet spot"[6]

[6] Sweet spot: Viable, non-decoupling region in MSSM parameter space.

Effective Field Theory[7]

[7] For list of all gauge inv. $SU(3) \times SU(2) \times U(1)$, see Leung, et. al, Z. Phys. C31, 433 (1986). For more recent treatments, see Hagiwara, et. al, Phys. Rev. D48, 2182 (1993); Gunion, et. al, Phys. Lett. 77, 5172 (1996); T. Han, et. al, Phys. Rev. D61, 015006 (1999); Phlen, et. al, Phys. Rev. Lett. 88, 051801 (2002); T. Han, et. al, Phys. Rev. D73, 055010 (2006); Naive Dimension Analysis: H. Georgi, et. al, Nucl. Phys. 234B, 189 (1984) A. Cohen, et. al, Phys. Lett. B412 301 (1997); M. Luty Phys. Rev. D57 1531 (1998);

Effective Field Theory (EFT)

- Effective Field Theory (EFT) is a powerful method of accounting for phenomena when participating degrees of freedom i.e., particles, are much heavier than momentum transfer.

- It entails multiplying desired no. of SM-fields and normalizing by energy cutoff[8], while ensuring that desired conservation laws are maintained but not renormalizable.

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{Eff.}, \quad \mathcal{L}_{Eff.} = \sum_i \frac{f_i}{\Lambda^2}\mathcal{O}_i$$

- E.g. Fermi's Theory of $\beta-$decay is a "dimension six operator" that respects $U(1)_{EM}$ and energy transfer $q \sim m_n - m_p \approx 1$ MeV

$$\underbrace{\mathcal{L}}_{[GeV]^4} = \overbrace{\underbrace{G_F}_{[GeV]^{4-3-3=-2}}}^{f_F/\Lambda^2} \times \overbrace{\underbrace{(\overline{n}\gamma^{\mu}p)}_{[GeV]^{2\times 3/2=3}} \times \underbrace{(\overline{\nu}\gamma_{\mu}e)}_{[GeV]^3}}^{\mathcal{O}_F}$$

[8] Energy cutoff = When theory is no longer sensible

Effective Field Theory: Modeling $t \to Wbh$

- 13 dim-six operators[9] contribute to $t \to Wbh$ by modifying the tth, tWb, WWh, or the (sexy) 4-point $tWbh$ vertex.
- ATLAS, CMS,[10] and oblique parameters[11] constrain all but 4[12] operators that affect only tth vertexes:

$$\begin{aligned}
\mathcal{O}_{t1} &= \left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)\left(\overline{q_L}t_R\tilde{\Phi} + \tilde{\Phi}^\dagger\overline{t_R}q_L\right) \\
\overline{\mathcal{O}}_{t1} &= i\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)\left(\overline{q_L}t_R\tilde{\Phi} - \tilde{\Phi}^\dagger\overline{t_R}q_L\right) \\
\overline{\mathcal{O}}_{t2} &= \left[\Phi^\dagger(D_\mu\Phi) + (D_\mu\Phi)^\dagger\Phi\right](\overline{t_R}\gamma^\mu t_R) \\
\overline{\mathcal{O}}^{(1)}_{\Phi q} &= \left[\Phi^\dagger(D_\mu\Phi) + (D_\mu\Phi)^\dagger\Phi\right](\overline{t_L}\gamma^\mu t_L),
\end{aligned}$$

where $\Phi^T = 1/\sqrt{2}(0, v+h)$ is SM Higgs doublet,

$$q_L^T = (t_L, b_L), \quad \tilde{\Phi} = i\sigma_2\Phi^*, \quad t_{L(R)} = P_{L(R)}t$$

[9] See refs. two slides ago.
[10] [G. Aad. et al. [ATLAS] (2012), S. Chatrchyan, et al. [CMS] (2012)]
[11] [Peskin, Takeuchi (1990)]
[12] Low hanging fruit.

EFT: Modeling $t \to Wbh$

After EWSB, the tth interaction Lagrangian is

$$\mathcal{L}_{tth} = -\bar{t}\left(g^{SM} - g^{S} - ig^{P}\gamma^{5}\right) th + \left(\frac{\partial_\mu h}{v}\right) \bar{t}\gamma^{\mu}(g^{L}P_{L} + g^{R}P_{R})t,$$

where g^{SM} is the SM tth coupling

$$g^{SM} = \frac{gm_t}{2M_W} \sim 0.7,$$

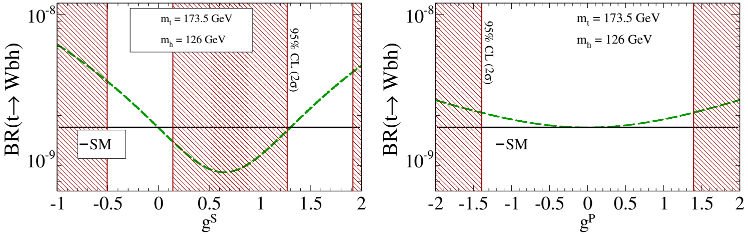
and the anomalous couplings, g^X are

$$g^{S} = \frac{f_{t1}}{\sqrt{2}}\frac{v^2}{\Lambda^2}, \quad g^{P} = \frac{\overline{f_{t1}}}{\sqrt{2}}\frac{v^2}{\Lambda^2}, \quad g^{L} = \overline{f_{\Phi q}^{(1)}}\frac{v^2}{\Lambda^2}, \quad g^{R} = \overline{f_{t2}}\frac{v^2}{\Lambda^2}$$

After varying $g^{S,P,L,R}$, we have some interesting results.

EFT Scalar and Pseudoscalar Couplings

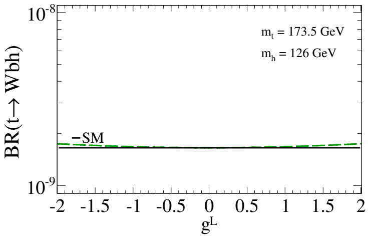
Branching Ratio as a function of EFT coupling, $g^{S,\ P}$.
Black line is prediction for SM Higgs with SM couplings.



- g^S is simply a strict enhancement/suppression of g^{SM}, i.e., $g^{Eff} = g^{SM} - g^S$. Minimum occurs at $g^S = g^{SM} \approx 0.7$.
- g^P contributes quadratically, i.e., $g^{Eff} = \sqrt{g^{SM\ 2} + g^{P\ 2}}$, and gives a near symmetric $g^{Eff.}$ dependence.

EFT LH and RH Vector Couplings

Branching Ratio as a function of EFT coupling, $g^{L,\ or\ R}$.
Black line is prediction for SM Higgs with SM couplings.



- Enhancements grow slower than g^S due to factor of h/v in leading diagram.
- Anomalous RH vector current grows faster than LH because off-shell top quark flips to RH-helicity and $\mathcal{M}_{tth} \propto m_t$
- In anomalous LH vector current, off-shell top remains in LH-helicity and $\mathcal{M}_{tth} \propto t^*$

LHC Prospects

The SM rate is small but the full LHC 14 data set may be enough.

$$\sigma_{LHC\ 14} = \sigma^{NLO}_{LHC\ 14}(t\bar{t}) \times BR(t \to Wbh) \times 2 \times BR(W \to \mu\nu_\mu) \times 2 \\ \times BR(h \to \underbrace{WW + ZZ + jj}_{21\%(WW)+2\%(ZZ)+54\%(b\bar{b})+4\%(c\bar{c})+4\%(gg)=85\%})$$

Model	$BR(Wbh)$	$\sigma_{LHC\ 14}$	$N(3\ \text{ab}^{-1})$	$N(10\ \text{ab}^{-1})$
SM	1.65×10^{-9}	0.5 ab	1.5	5
2HDM/EFT	$\sim 10^{-9}$	0.3 ab	0.9	3
2HDM/EFT	$\sim 10^{-8}$	3 ab	9	30
2HDM	$\sim 10^{-7}$	30 ab	90	300

Conclusion

Summary : We have systematically studied the rare $t \to Wbh$ decay process in the context of the SM, the 2HDM(II), and EFT

- The SM rate is small but observable with full LHC 14 data set.
- EFT can easily drive up the rate
- 2HDM can enhance $(m_A, m_{H_2} < 120$ GeV$)$ or suppress the rate, requiring $\mathcal{O}(10)$ ab data set.

Stay Tuned :

- 09:00(TH) Working Group Session, 3: Top Quark Couplings
- 11:10(TH) CMS, FCNC and top rare decays
- 11:50(TH) ATLAS, tt+V and tt+gamma

Plug :

- Snowmass 2013 Young Physicist Movement http://snowmassyoung.hep.net/
- Young people, visit the site!